

O VI High Velocity Clouds: Where and What are They?

Kenneth R. Sembach

*Department of Physics & Astronomy, The Johns Hopkins University,
 3400 N. Charles Street, Baltimore, MD 21218*

Abstract. Our view of the high velocity cloud (HVC) system is changing dramatically with new observations from the *Far Ultraviolet Spectroscopic Explorer* mission and the Space Telescope Imaging Spectrograph on-board the *Hubble Space Telescope*. In particular, the detection of O VI absorption indicates that many HVCs have a hot, collisionally-ionized component in addition to the neutral gas detected in H I 21 cm emission. A better understanding of the ionization of this gas will help to determine the distances of some HVCs, as well as constrain the properties of a hot Galactic corona or Local Group medium. In this article, I briefly summarize some recent observations of O VI HVCs.

1. Introduction

It is my sincere pleasure to be able to present a talk at this conference in honor of Dr. Ray Weymann and his many contributions to astronomy. Rather than delve into a lengthy description of the known properties of high velocity clouds (HVCs), I will instead concentrate on some recent observational results that provide new information about HVCs that you may not have heard about before. I hope that this talk stimulates as much discussion about what we do not yet know about HVCs as it does about what we do know.

First, a very brief introduction to HVCs is in order. Despite their simple name, high velocity clouds have a long history of being contentious subjects of debate. Most HVCs have been identified through their H I 21 cm emission, which occurs at velocities well outside the range expected for typical interstellar clouds (typically, $|v_{HVC}| \sim 100 - 350 \text{ km s}^{-1}$). Within the last decade it has also been possible to study HVCs in absorption using ultraviolet spectrographs in space. Some of these clouds have been confirmed to be Galactic in nature since they are observed in the absorption-line spectra of stars at known distances. Others, such as the Magellanic Stream, are clearly located outside the normally recognized confines of the Galaxy. The case for an extragalactic origin of some H I HVCs has been presented recently by several authors (e.g., Blitz et al. 1999; Braun & Burton 1999; see also Gibson et al. - this volume - for additional references and a concise discussion of the pros and cons of an extragalactic location for HVCs). There are several comprehensive reviews of the sky distribution of HVCs and the known properties and locations of some of the better-studied clouds (Wakker & van Woerden 1997; Wakker 2001).

2. Ionized Gas: A New Perspective

Much of what is known about the kinematics, morphologies, and angular projections of HVCs onto the sky comes from H I 21 cm emission studies. However, many HVCs are now known to contain significant quantities of ionized gas. The ionized gas has been traced through both its H α emission (e.g., Bland-Hawthorn et al. 1998; Tufté, Reynolds, & Haffner 1998) and its absorption-line signatures in ionized species such as C III-IV, Si III-IV, and O VI (e.g., Sembach et al. 1999; Sembach et al. 2000).

The existence of an ionized component to the high velocity cloud system has several obvious ramifications. First, it indicates that there is material in a form that heretofore has not been readily observed. The extent of this ionized gas is presently unknown, although new H α imaging techniques hold great promise for revealing very low levels of emission regardless of the distances of the clouds (e.g., Glazebrook & Bland-Hawthorn 2001). Second, the ionization of this gas must be maintained by an energy source either internal or external to the HVCs. Since there are as yet no known stars that emit significant numbers of ionizing photons directly associated with HVCs, it seems likely that most of the energy must come either from photons emanating from somewhere outside the clouds or from collisional processes occurring between the clouds and other interstellar or intergalactic material. Third, the detection of high velocity O VI along many sight lines through the Milky Way halo (Sembach et al. 2000, 2001c; Savage et al. 2001) suggests that there may be dynamical interactions between some HVCs and a hot Galactic corona or Local Group medium. It is to this third point that the rest of this article is devoted.

3. O VI High Velocity Clouds

The study of highly ionized high velocity gas traced through O VI absorption became possible with the commissioning of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) in late 1999 (Moos et al. 2000)¹. Conversion of O V into O VI requires ~ 114 eV, an energy well above the He II absorption edge at 54.4 eV. O VI is an excellent tracer of collisional processes at temperatures $T \sim (1 - 5) \times 10^5$ K (Sutherland & Dopita 1993). O VI has an observable resonance doublet at 1031.926, 1037.617 Å. Of the two lines, the stronger (1031.926 Å) line is more frequently observed since the weaker line is often blended with other atomic and molecular lines (e.g., C II λ 1036.337, C II* λ 1037.018, H₂ (5–0) R(1) λ 1037.149 and H₂ (5–0) P(1) λ 1038.157). High velocity absorption in the O VI 1031.926 Å line can be blended with nearby H₂ (6–0) P(3) absorption at 1031.191 Å (-214 km s^{−1}) and (6–0) R(4) absorption at 1032.349 Å ($+122$ km s^{−1}). When a comparison between both members of the O VI doublet has been possible in the Milky Way halo and HVC studies to date, the results have indicated that there is no unresolved saturated structure in the lines at *FUSE*

¹Additional information about the general usefulness of *FUSE* data for HVC studies can be found in Sembach (1999).

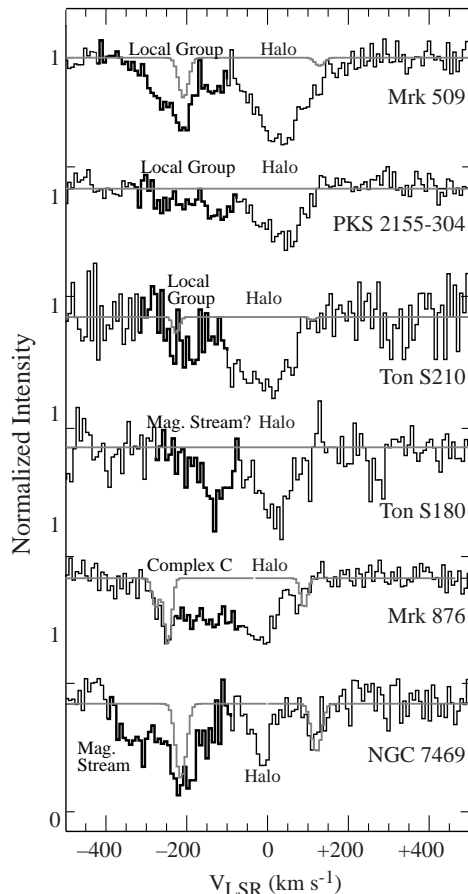


Figure 1. O VI HVCs observed by *FUSE* along 6 sight lines (from Sembach et al. 2000). The O VI $\lambda 1031.926$ data are shown, together with a model of the Milky Way H₂ absorption expected in the (6–0) P(3) and R(4) lines (solid grey curves). Milky Way disk and halo absorption occurs along each sight line at velocities of about -100 to $+100$ km s^{−1}. The data have a velocity resolution (FWHM) of 20 – 25 km s^{−1}. A general location is indicated for each HVC delineated by the thick black lines. All of these HVCs are located either in the very distant Galactic halo or outside the Galaxy.

resolution (FWHM ≈ 20 – 25 km s^{−1}). This result is consistent with production of the O VI in collisionally-ionized gas at temperatures $T \geq 10^5$ K.

3.1. Examples

Examples of the O VI $\lambda 1031.926$ absorption in several high velocity clouds observed by *FUSE* are shown in Figure 1. These include the Magellanic Stream, Complex C, and HVCs believed to be located outside the Galaxy in the Local Group. Absorptions from both the Milky Way halo and the high velocity gas are evident. The faint solid grey line overplotted on each spectrum is a model of the H₂ absorption features expected in the velocity range shown (see Sembach et al. 2000). The O VI HVCs in Figure 1 are relatively well-separated from the lower velocity absorption. They occur at velocities similar to those of lower ionization

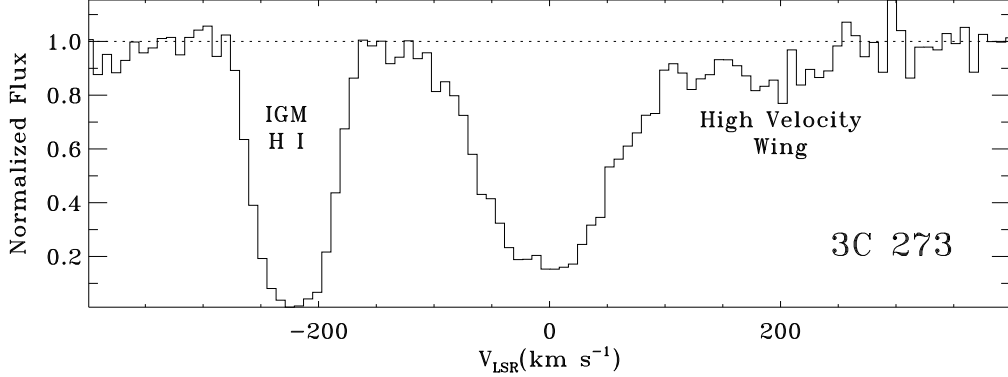


Figure 2. Galactic O VI $\lambda 1031.926$ absorption toward 3C 273 (Sembach et al. 2001c). Note the high velocity wing at $v_{LSR} > 100 \text{ km s}^{-1}$. This absorption wing is observed only in O VI. The high velocity O VI traces hot material flowing out of the Galactic disk into the halo.

species (such as C IV or H I) and have strengths ranging from ≈ 0.3 (Ton S210) to ≈ 1.7 (NGC 7469) times the strength of the Milky Way halo absorption.

A second type of high velocity gas detected in O VI absorption occurs along some sight lines through the Milky Way halo. Figure 2 shows an example of a high velocity O VI absorption wing in the direction of 3C 273 (Sembach et al. 2001c). This feature is shallow and very broad, roughly 150 km s^{-1} in width. The absorption is present in data obtained in multiple *FUSE* channels and has no counterpart in lower ionization species. The column of O VI contained in this wing is approximately 10% of the total O VI column along the sight line. These high velocity wings are seen along several other sight lines currently under study and will be described in a forthcoming paper. The favored interpretation for the high velocity wing toward 3C 273 is that the absorption traces the expulsion of hot gas out of the Galactic disk into the halo in the Loop I / Loop IV region of the sky. The high ion ratios observed are consistent with the expectations for radiatively cooling gas in a fountain flow or supernova remnant (see Sembach et al. 2001c).

3.2. Relationship to H I and Lower Ionization Species

Most of the O VI HVCs studied so far have readily identifiable counterparts in H I. In the case of at least one large HVC, that of Complex C, the O VI absorption along several sight lines through the HVC traces the H I velocity structure quite well. Figure 3 shows the O VI $\lambda 1031.926$ absorption toward four Complex C sight lines together with the H I 21 cm emission profiles² observed with the NRAO 140-foot telescope and the Fe II $\lambda 1144.938$ profiles observed with *FUSE*. The H I emission velocities and strengths change substantially across Complex C. For the four sight lines shown, the Complex C H I velocities range

²These H I 21 cm data are from an unpublished survey by Murphy, Sembach, and Lockman.

from $\approx -174 \text{ km s}^{-1}$ toward Mrk 876 to $\approx -105 \text{ km s}^{-1}$ toward Mrk 817. (This sight line pair has the smallest angular separation of the set, $\Delta \approx 5.3^\circ$.) The O VI $\lambda 1031.926$ absorption profiles clearly reveal gas at the Complex C velocities traced by H I and Fe II. The O VI profiles are smoother than the H I emission or low ionization absorption, but track the neutral gas well; there appears to be a strong correlation between the O VI velocity structure and the velocity structure of lower ionization stages. The O VI HVC line strength is roughly comparable along the Mrk 817, Mrk 279, and PG 1259+593 sight lines, while the strength toward Mrk 876 is about a factor of two higher. The opposite is true for the HVC H I emission; the strength of the emission toward Mrk 876 is less than that along the other three sight lines.

We show a second comparison of the O VI and low ionization lines in another HVC in Figure 4. This HVC, observed along the NGC 1705 sight line ($l = 261.1^\circ, b = -38.7^\circ$), traces material associated with the Magellanic Stream near the LMC (see Sembach et al. 2001b). This HVC has a multi-component structure as revealed by the Space Telescope Imaging Spectrograph data shown in Figure 4. Multiple ionized gas components traced by Si III $\lambda 1206.500$ are spread over a velocity range of $\approx 140 \text{ km s}^{-1}$. The O VI absorption is centered near the velocity of the strongest low ionization component traced by the O I $\lambda 1302.168$ line. Furthermore, the O VI tracks closely the high velocity ($v_{\text{helio}} > 320 \text{ km s}^{-1}$) absorption wing seen Si III, suggesting either that there is a hot component of the cloud centered on the strongest low ionization component, or that there is a highly ionized leading edge to the cloud. The width of the O VI absorption (FWHM $\approx 83 \text{ km s}^{-1}$) is much broader than expected for a single-component gas at $T \sim 3 \times 10^5 \text{ K}$, suggesting that the O VI may trace multiple hot gas components or that the absorption is broadened by non-thermal motions having velocities on the order of 50 km s^{-1} .

4. Where are the O VI HVCs?

The answer to this question is still being sought. However, from the information that is now available, it seems quite likely that *some* of the O VI HVCs are tracing material in the vicinity of the Milky Way rather than material within the Milky Way. Several lines of evidence support this conclusion:

- 1) O VI absorption is observed in several large HVCs known to lie at large distances from the Galactic plane (e.g., the Magellanic Stream). Other excellent candidates for HVCs located in the distant Galactic halo or Local Group based on their ionization properties or abundances include the C IV HVCs toward Mrk 509 (Sembach et al. 1999) and Complex C (Wakker et al. 1999).
- 2) O VI has been observed in the compact HVC toward Ton S210 (see Figure 1). This detection is significant since many of the observed properties of compact HVCs are best described if they are extragalactic clouds within the Local Group. The compact HVCs have small angular sizes ($\sim 1^\circ$) and are isolated. Their velocity dispersion as a group of clouds is minimized in the Local Group Standard of Rest, and they have a spatial distribution similar to that of dwarf galaxies in the Local Group (Braun & Burton 1999). The compact HVC toward Ton S210 also has a sub-solar metallicity that is consistent with a location outside the Galaxy, although a more definitive measure of the metallicity is required to ex-

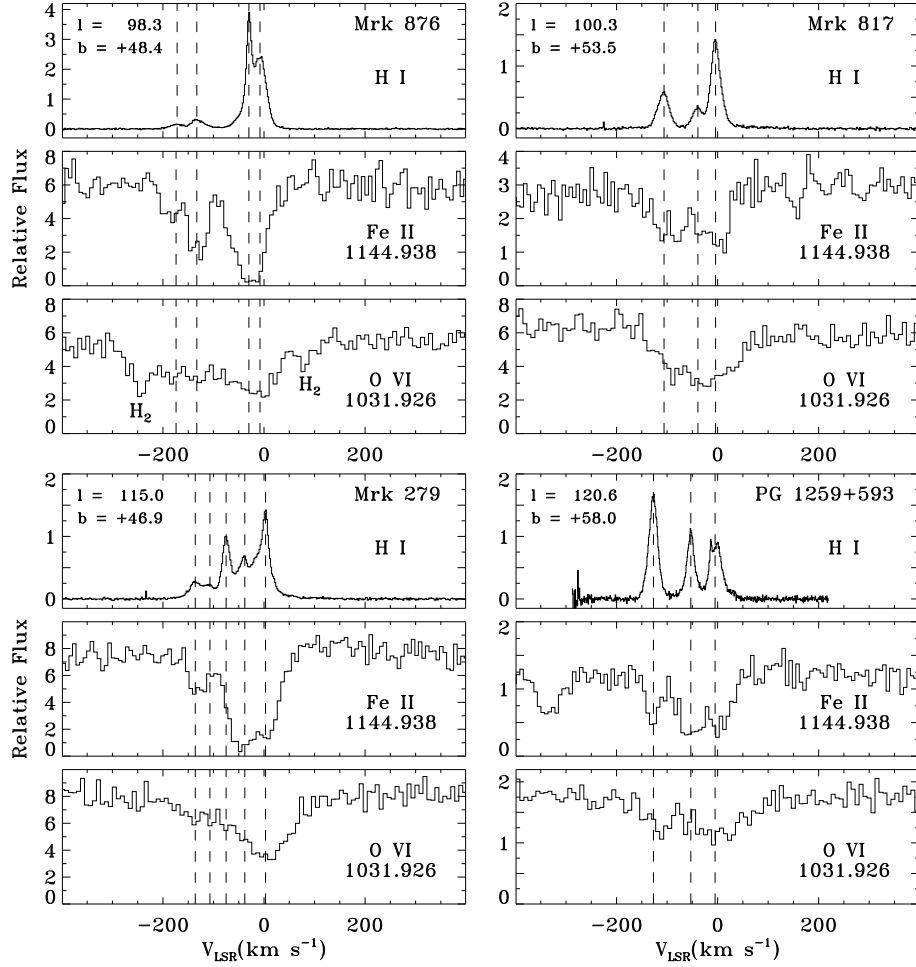


Figure 3. $\text{O VI } \lambda 1031.926$ and $\text{Fe II } \lambda 1144.938$ absorption toward four sight lines piercing through HVC Complex C. Also shown are the $\text{H I } 21\text{ cm}$ emission profiles observed along each sight line with the NRAO 140-foot telescope. High and low ion Complex C absorption features in the *FUSE* spectra at $v_{\text{LSR}} \leq -100\text{ km s}^{-1}$ are indicated by the left-most vertical lines. Milky Way ISM absorption and emission are present near $v_{\text{LSR}} = 0\text{ km s}^{-1}$. Differing amounts of intermediate velocity gas are also present along the four sight lines. Note that the bulk absorption velocities of the neutral and O VI -bearing gases are similar, suggesting that the highly ionized and neutral gases are in close proximity to each other.

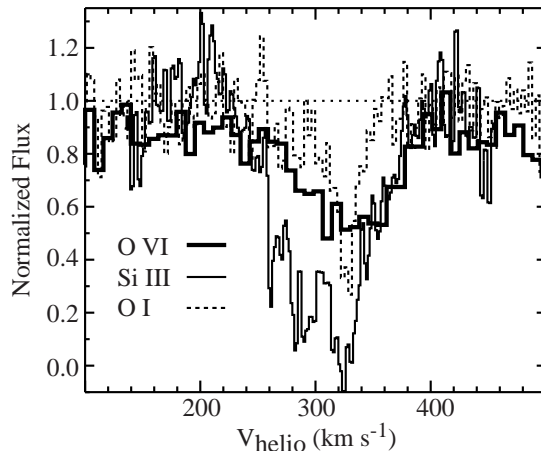


Figure 4. High velocity O VI $\lambda 1031.926$, Si III $\lambda 1206.500$, O I $\lambda 1302.168$ absorption in the HVCs toward NGC 1705. Note the multi-component structure of the ionized gas traced by Si III. The O VI absorption is roughly centered on the dominant neutral component traced by O I.

clude a Galactic location (Sembach et al. 2001a).

3) High velocity O VI absorption is observed along sight lines through the halo along extragalactic lines of sight (e.g., Sembach et al. 2000). A much larger sample currently being analyzed in conjunction with the Wisconsin group (Savage, Wakker, Richter) indicates that high velocity O VI along extended paths through the halo and Local Group is common. However, there have not yet been any definitive detections of high velocity O VI observed toward halo stars located within a few kiloparsecs of the Galactic plane – an early study by Zsargo et al. (2001, and work in preparation) of 10–12 sight lines shows no evidence of high velocity O VI.

Not all of the high velocity O VI is located at large distances from the Galactic plane. The kinematics and high ion ratios suggest a Galactic origin for the high velocity O VI wing toward 3C 273. Furthermore, O VI is observed at intermediate-high velocities in several other large-scale structures in both the Milky Way and the Magellanic Clouds: for example, the Scutum supershell (Sterling et al. 2001) and supernova remnant SNR 0057–7226 in the direction of HD 5980 in the SMC (Hoopes et al. 2001).

5. Ionization

The presence of O VI in HVCs indicates that the gas is collisionally ionized at temperatures of $\sim 10^5 - 10^6$ K. Photoionization by starlight is unlikely. Photoionization by the extragalactic ultraviolet background may produce some O VI, but not in the quantities observed. The typical O VI column densities predicted for large ($D > 10 - 20$ kpc) low density ($n \sim 10^{-4} \text{ cm}^{-2}$) clouds at $z \sim 0$ are of the order of 10^{13} cm^{-2} (see Sembach et al. 1999), an order of magnitude less than the typical column densities observed. The distances of the Magellanic

Stream and Complex C are not likely to be large enough to accommodate higher columns produced by photoionization.

The coincidence of neutral (or weakly ionized) gas at velocities similar to those of many of the O VI HVCs suggests that production of the O VI might involve contact interfaces between the cool / warm material and hot ($T \geq 10^6$ K) gas. This hotter gas may take the form of a pervasive, hot Galactic halo or Local Group medium with a density $n_H < 10^{-4}$ cm $^{-2}$. Alternatively, the O VI may trace cooling regions of hot gas structures associated with the assembly of the Milky Way. Additional STIS data for the O VI HVCs observed by *FUSE* would help to constrain the various ionization mechanisms in the clouds.

6. Acknowledgments

I would like to thank and acknowledge my collaborators on various aspects of this work, each of whom have contributed to the results presented in this paper: Blair Savage, Tim Heckman, Claus Leitherer, Brad Gibson, and Mary Putman. I also thank the *FUSE* Operations Team at the Johns Hopkins University for their outstanding efforts in making *FUSE* a superb far-ultraviolet observatory. Finally, I thank John Mulchaey and the other workshop organizers for making this a truly enjoyable and memorable meeting.

References

- Bland-Hawthorn, J., Veilleux, S., Cecil, G.N., Putman, M.E., Gibson, B.K., & Maloney, P.R. 1998, MNRAS, 299, 611
- Blitz, L., Spergel, D.N., Teuben, P. Hartmann, D., & Burton, W.B. 1999, ApJ, 514, 818
- Braun, R., & Burton, W.B. 1999, A&A, 341,437
- Glazebrook, K., & Bland-Hawthorn, J. 2001, PASP, 113, 197
- Hoopes, C., Sembach, K.R., Howk, J.C., & Blair, W.P. 2001, ApJ, in press [astro-ph/0108049]
- Moos, H.W., Cash, W.C., Cowie, L.L., et al. 2000, ApJ, 538, L1
- Savage, B.D., et al. 2001, in preparation
- Sembach, K.R. 1999, in the proceedings of the Stromlo Workshop on High Velocity Clouds, eds. B.K. Gibson & M.E. Putman, ASP Conf. Series 166, 243
- Sembach, K.R., Howk, J.C., Savage, B.D., Shull, J.M., & Oegerle, W.R. 2001c, ApJ, in press [astro-ph/0108047]
- Sembach, K.R., Gibson, B.K., Fenner, Y., & Putman, M.E. 2001a, ApJL, submitted
- Sembach, K.R., Heckman, T.M., Leitherer, C., et al. 2001b, in prep
- Sembach, K.R., Savage, B.D., Jenkins, E.B., et al. 2000, ApJ, 538, L31
- Sembach, K.R., Savage, B.D., Lu, L., & Murphy, E.M. 1999, ApJ, 515, 108
- Sterling, N., Savage, B.D., Richter, P., Fabian, D., & Sembach, K.R. 2001, ApJ, submitted

- Sutherland, R. S., & Dopita, M. A. 1993, *ApJS*, 88, 253
- Tufte, S.L., Reynolds, R.J., & Haffner, L.M. 1998, *ApJ*, 504, 773
- Wakker, B.P. 2001, *ApJS*, in press [astro-ph/0102147]
- Wakker, B.P., Howk, J.C., Savage, B.D., et al. 1999, *Nature*, 402, 388
- Wakker, B.P., & van Woerden, H. 1997, *ARA&A*, 35, 217
- Zsargo, J., Sembach, K.R., Savage, B.D., and Hoopes, C.G. 2001, *BAAS*, 198, 6001